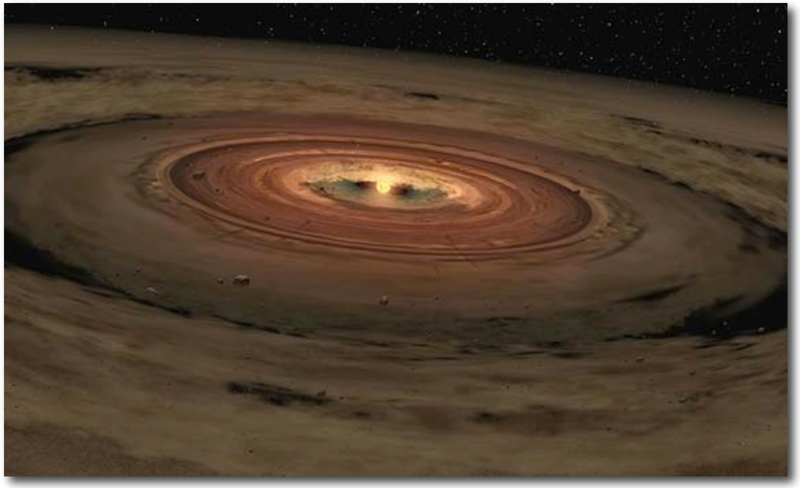
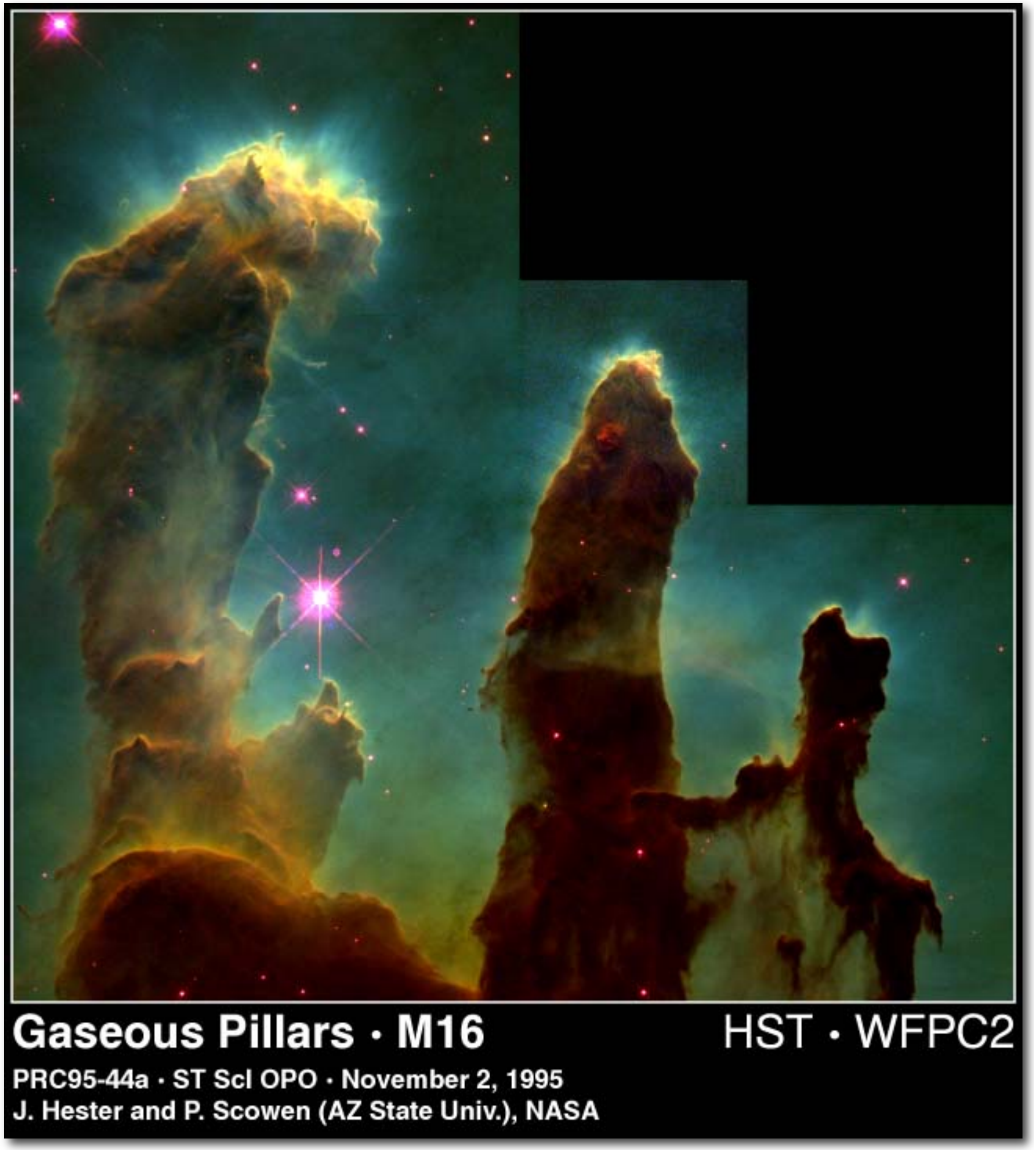
Solar System/Planet Formation

Gas Clouds to Stars/Planets

Planet Migration

Satellite Formation





Formation of the Solar System

STEPS:

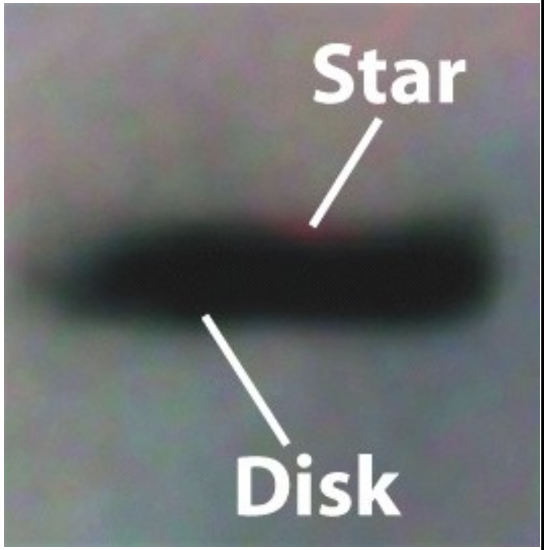
CLOUD COLLAPSE

↓

ROTATING DISK

EVIDENCE:

- **young stars seen in collapsing gas clouds**
- **planets orbit in same direction and same plane**
- **Sun and planets rotate in same direction**
- **disks seen around other stars**

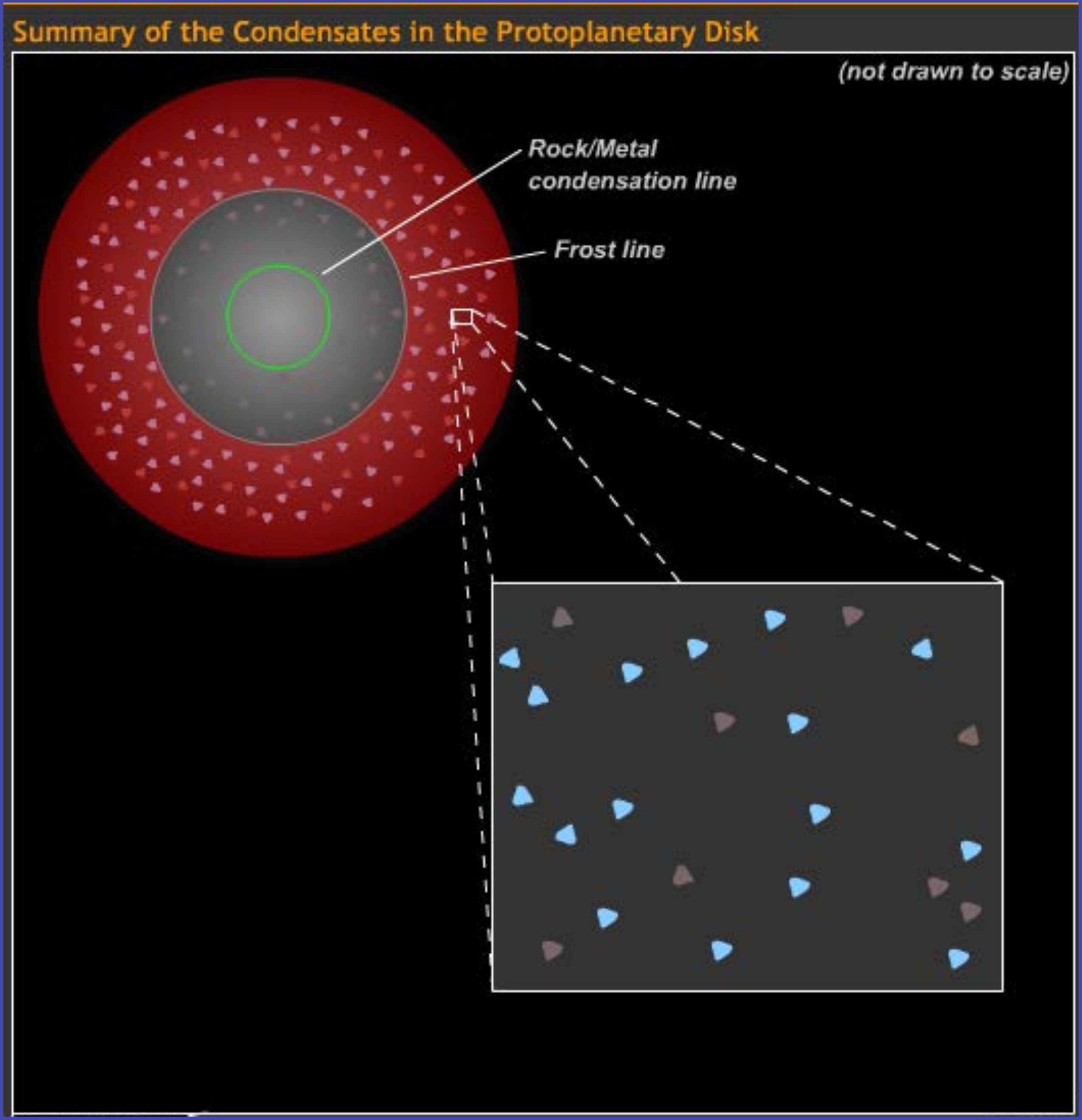


Raw Materials for Planets

The most abundant raw materials:

1. **H, He gases**
2. **"ices" (hydrogen compounds)**
3. **rock and metal**

	Examples	*Typical Condensation Temperature*	*Relative Abundance (by mass)*
Hydrogen and Helium Gas 	hydrogen, helium	do not condense in nebula	98%
Hydrogen Compounds 	water (H_2O) methane (CH_4) ammonia (NH_3)	<150 K	1.4%
Rock 	various minerals	500–1,300 K	0.4%
Metals 	iron, nickel, aluminum	1,000–1,600 K	0.2%



- Tiny 'dirt' particles formed from condensed rock/metal

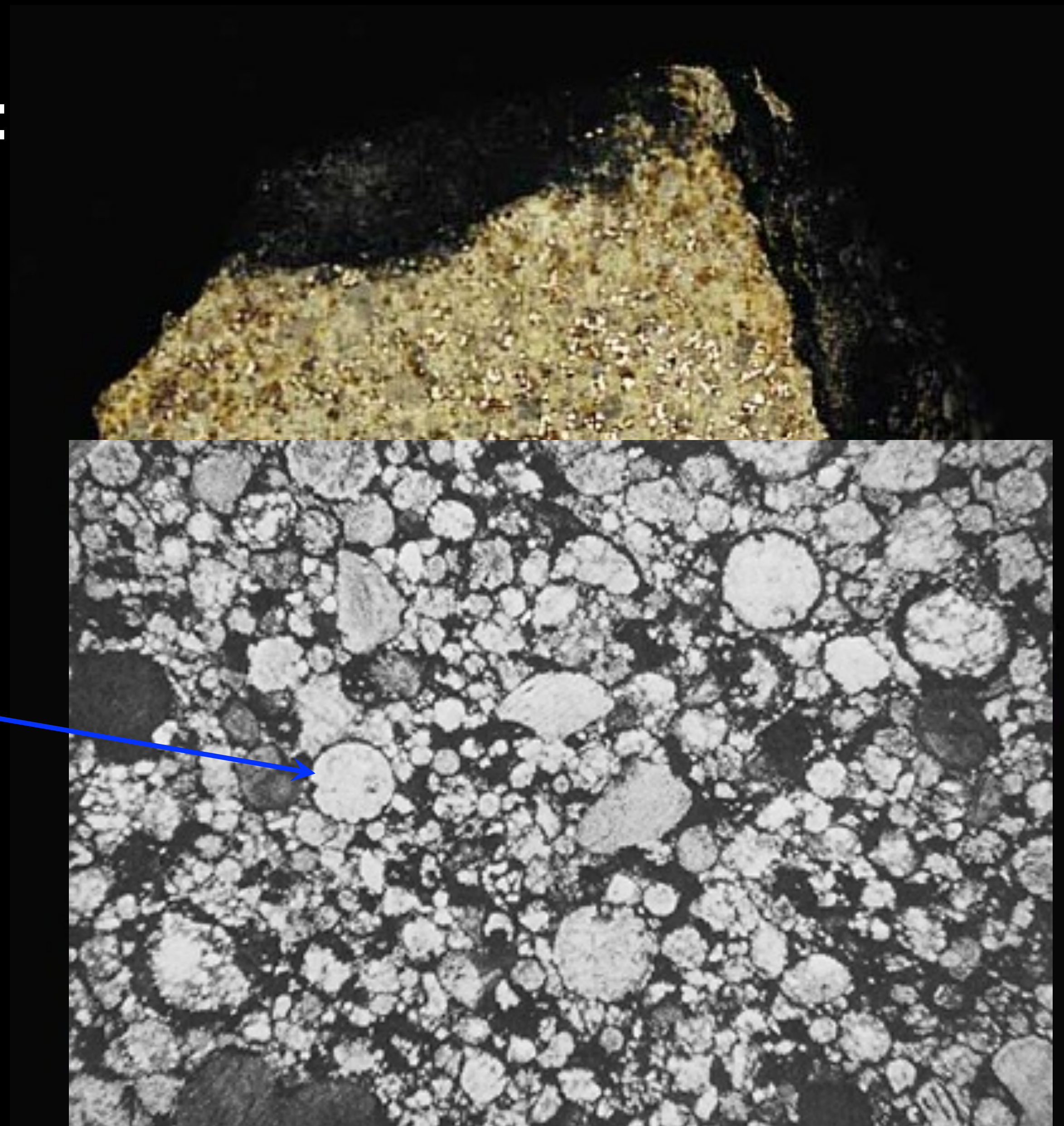
- Tiny <u>ice crystals</u> condensed from hydrogen compounds like water… but ONLY far from Sun due to thermal gradient

Examples of Condensation

Inner solar system:

↔ **rocky, metallic dust condensed together into small objects**

meteorite cut-away:



Formation of the Solar System

STEPS:

CLOUD COLLAPSE

↓

ROTATING DISK

↓

CONDENSATION

EVIDENCE:

CLOUD COLLAPSE:
- **young stars seen in collapsing gas clouds**

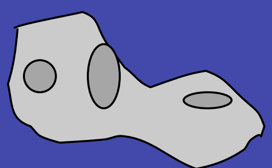
ROTATING DISK:
- **planets orbit in same direction and same plane**
- **Sun and planets rotate in same direction**
- **disks seen around other stars**

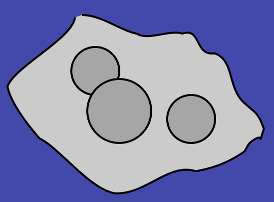
CONDENSATION:
- **terrestrial planets and asteroids found near Sun**
- **jovian planets, icy moons, comets found farther away**

Accretion

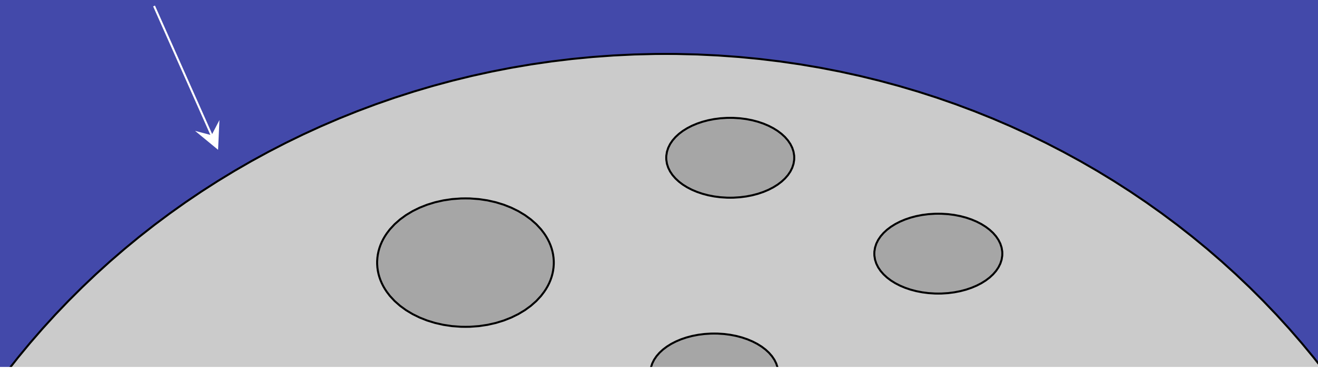
"Sticky" collisions of dust and snowflakes make bigger particles:

Planetesimals (like asteroids and comets: several km across) slowly form, until gravity is strong enough to help pull them together:

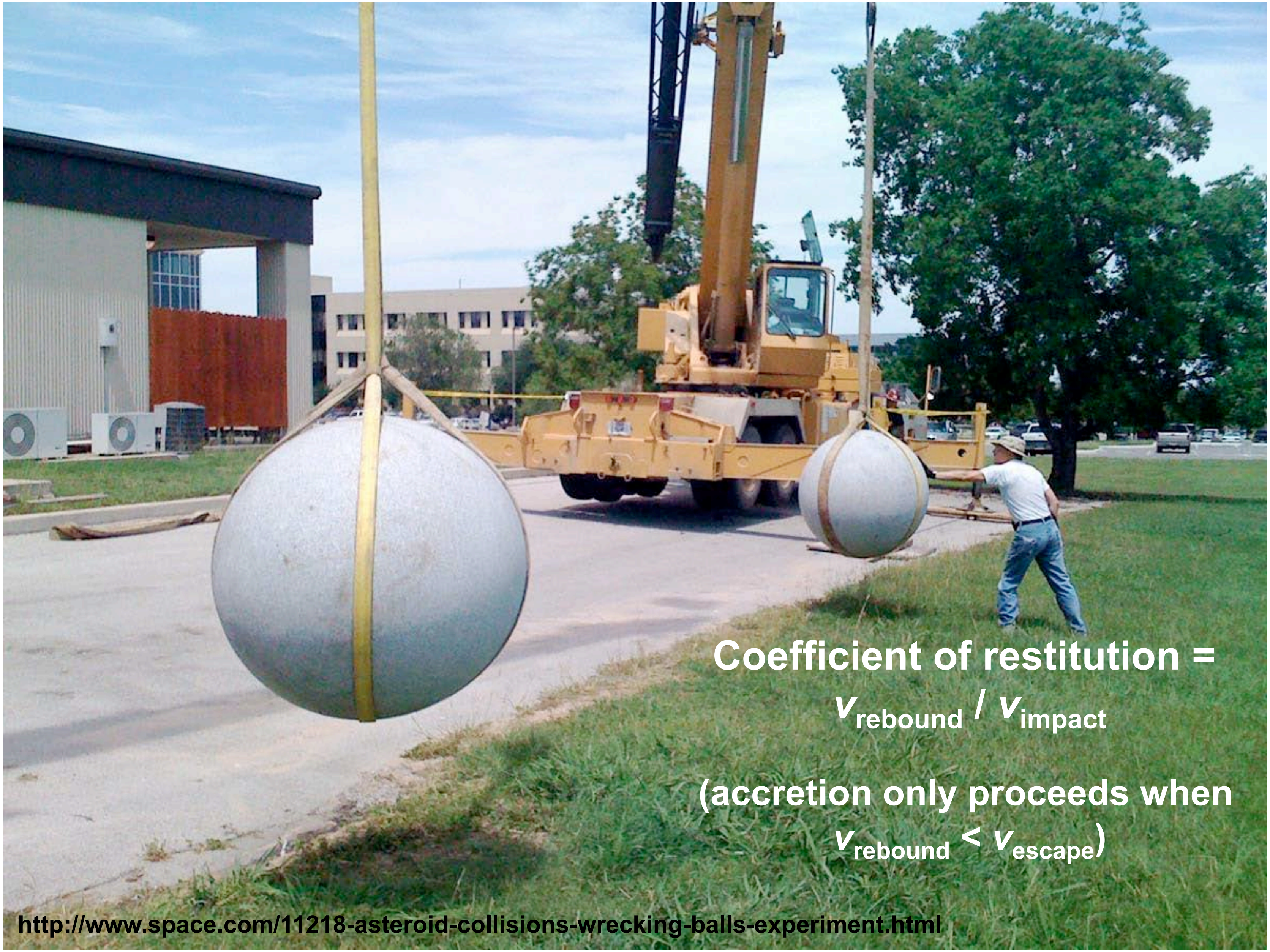




Larger protoplanets slowly form from these collisions:



Elastic or inelastic collisions?

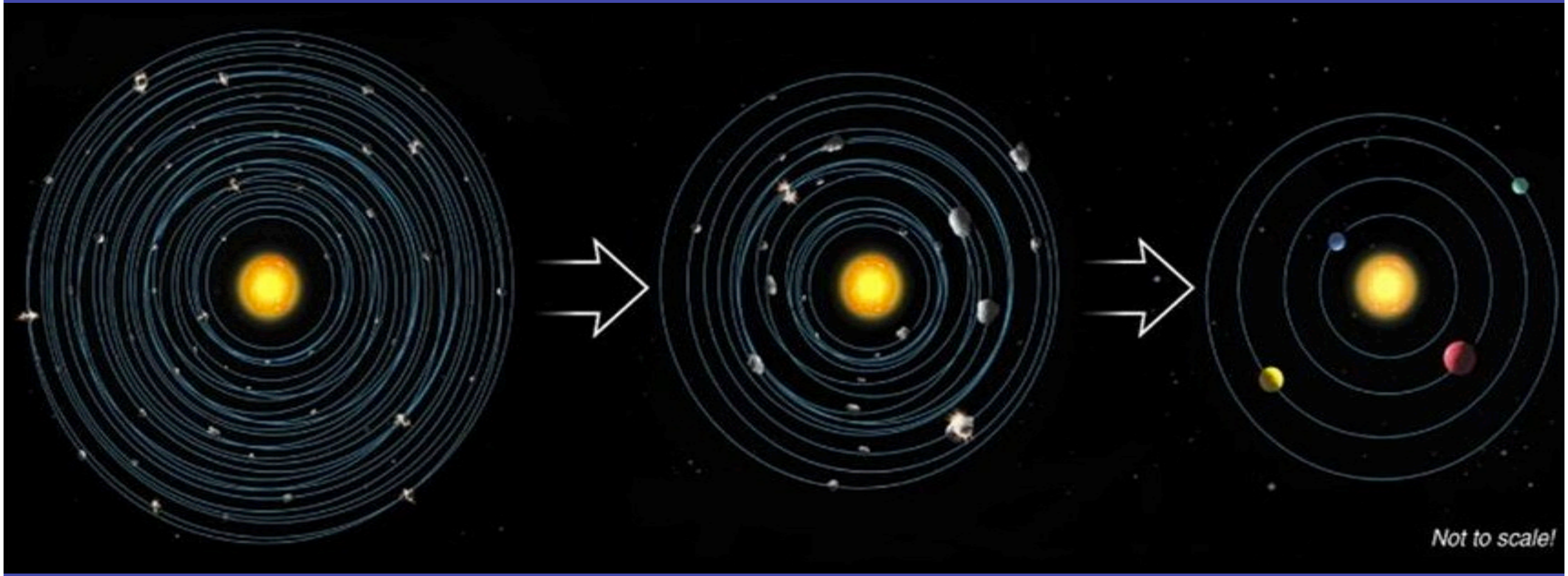


Coefficient of restitution = $v_{rebound}$ / v_{impact}

(accretion only proceeds when $v_{rebound} < v_{escape}$)

http://www.space.com/11218-asteroid-collisions-wrecking-balls-experiment.html

Accretion



- many small objects collected into just a few large ones
- collisions become less frequent as more material becomes ‘stuck’ together

Formation of the Solar System

STEPS:

EVIDENCE:

CLOUD COLLAPSE

- **young stars seen in collapsing gas clouds**

ROTATING DISK

- **planets orbit in same direction and same plane**
- **Sun and planets rotate in same direction**
- **disks seen around other stars**

CONDENSATION

- **terrestrial planets and asteroids found near Sun**
- **jovian planets, icy moons, comets found farther away**

ACCRETION

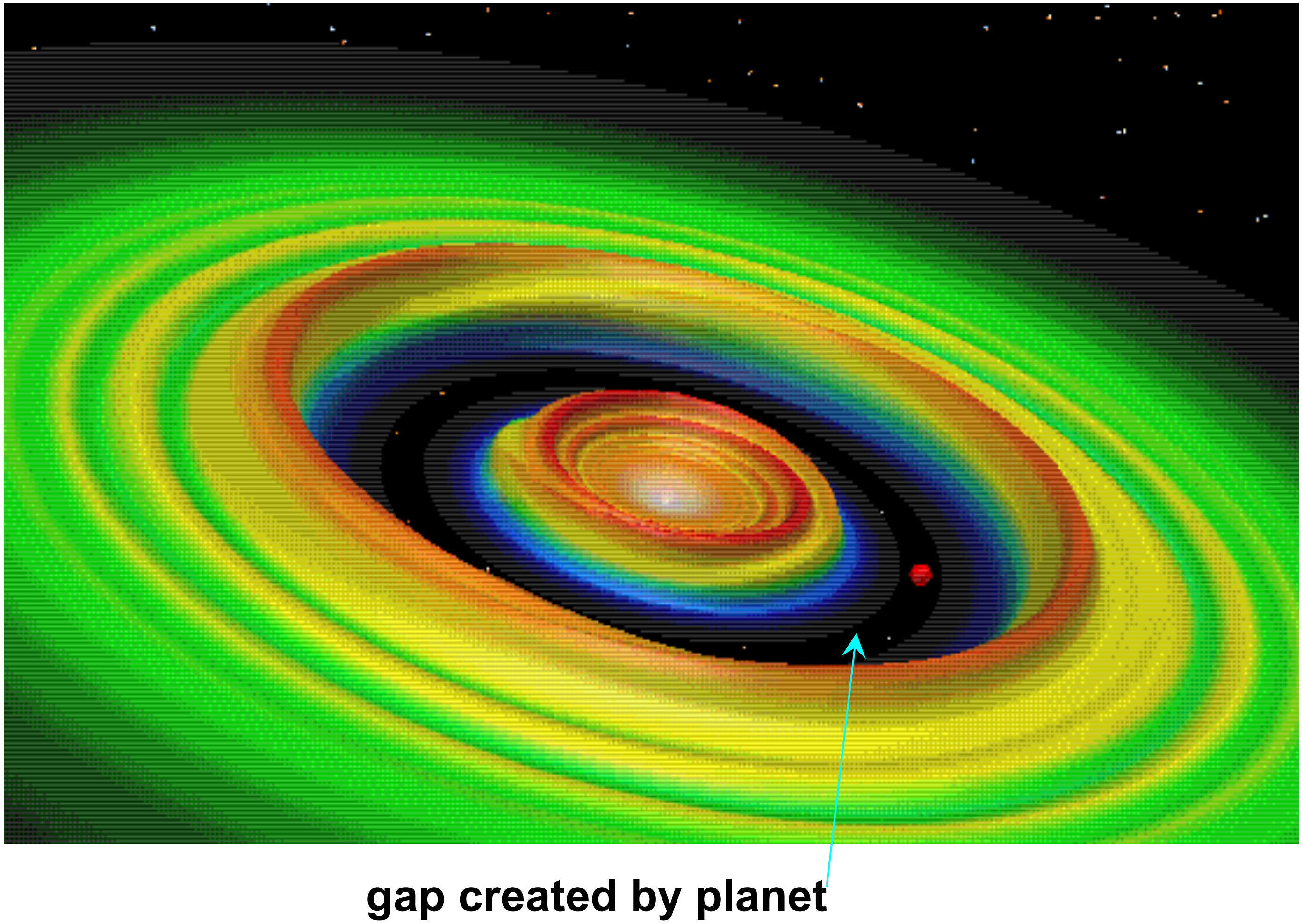
- **many meteorites are made of smaller bits**
- **heavy cratering on oldest planet surfaces**
- **asteroids, comets are "leftovers"**

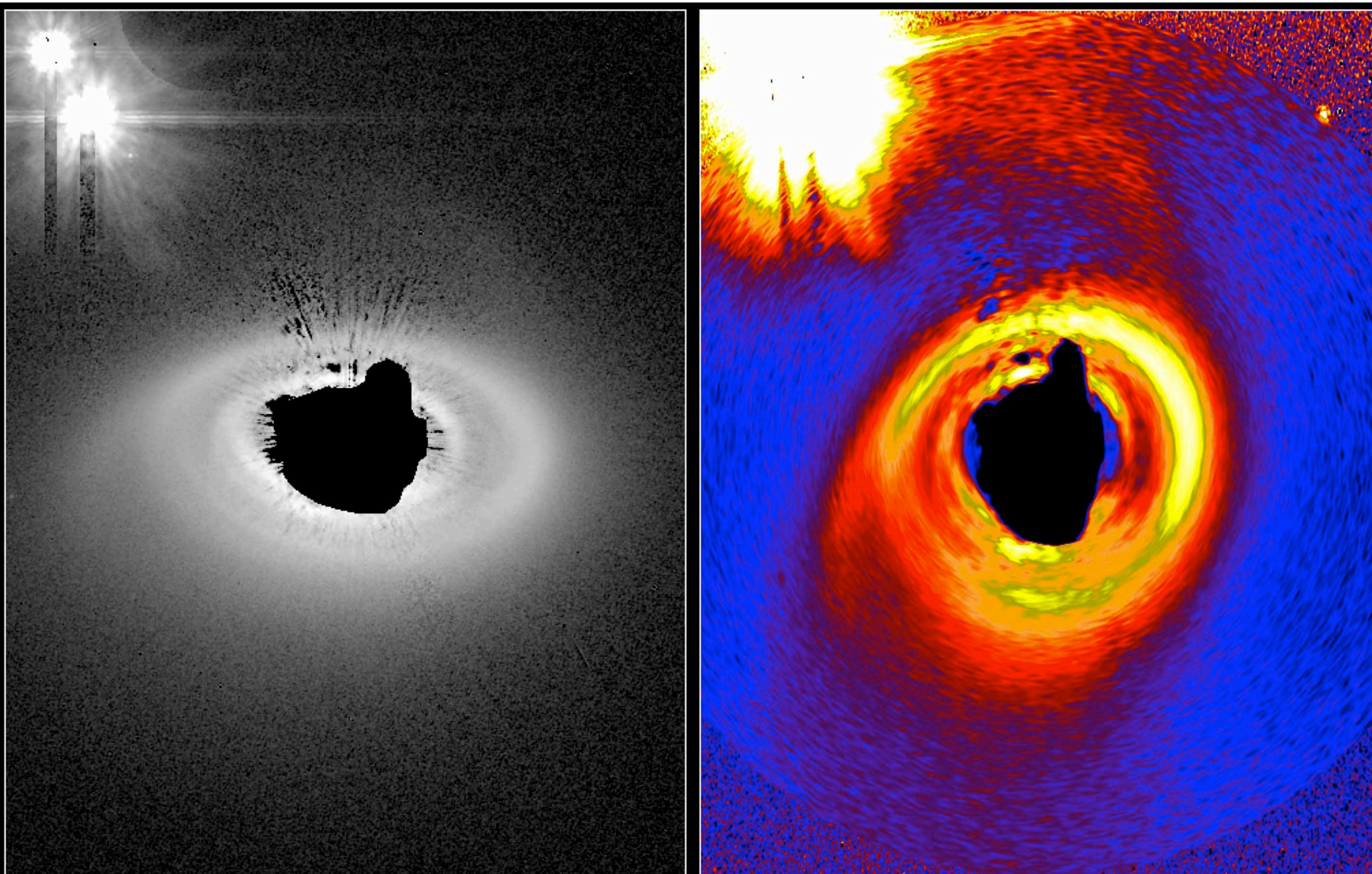
Gas Capture

Cores of jovian planets are large enough (≥ ~10 M_{Earth}) that <u>their gravity captures and holds gas</u> (hydrogen and helium)

→ Uranus and Neptune may have reached this core size too late to capture substantial gas before it was blown out of the solar system

<u>Computer simulation:</u>





HD 141569 Circumstellar Disk

Hubble Space Telescope ▪ ACS HRC Coronagraph

Formation of the Solar System

STEPS: / **EVIDENCE:**

CLOUD COLLAPSE

- young stars seen in collapsing gas clouds

ROTATING DISK

- planets orbit in same direction and same plane
- Sun and planets rotate in same direction
- disks seen around other stars

CONDENSATION

- terrestrial planets and asteroids found near Sun
- jovian planets, icy moons, comets found farther away

ACCRETION

- many meteorites are made of smaller bits
- heavy cratering on oldest planet surfaces
- asteroids, comets are "leftovers"

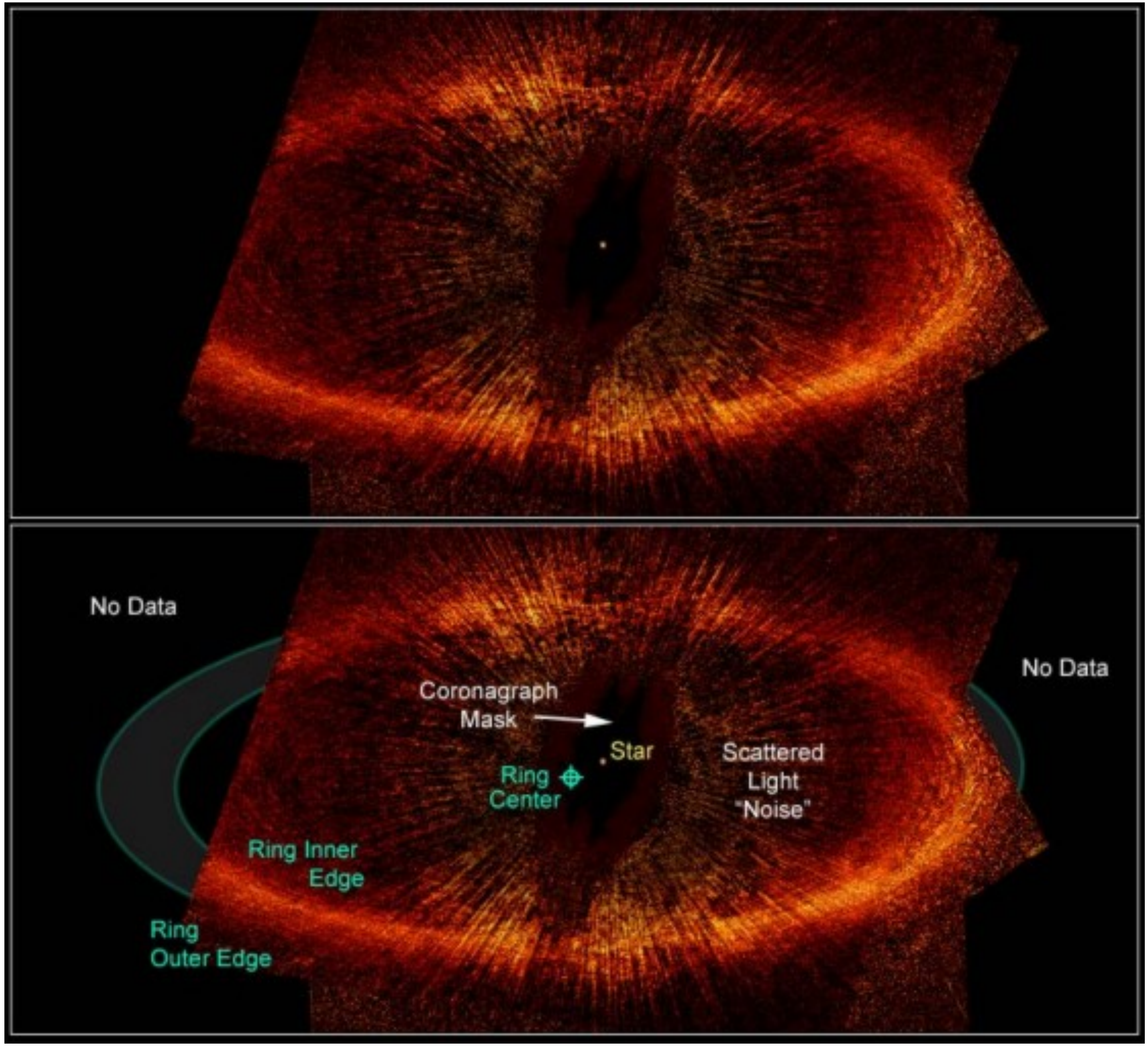
GAS CAPTURE?

- Jupiter, Saturn are mostly hydrogen and helium

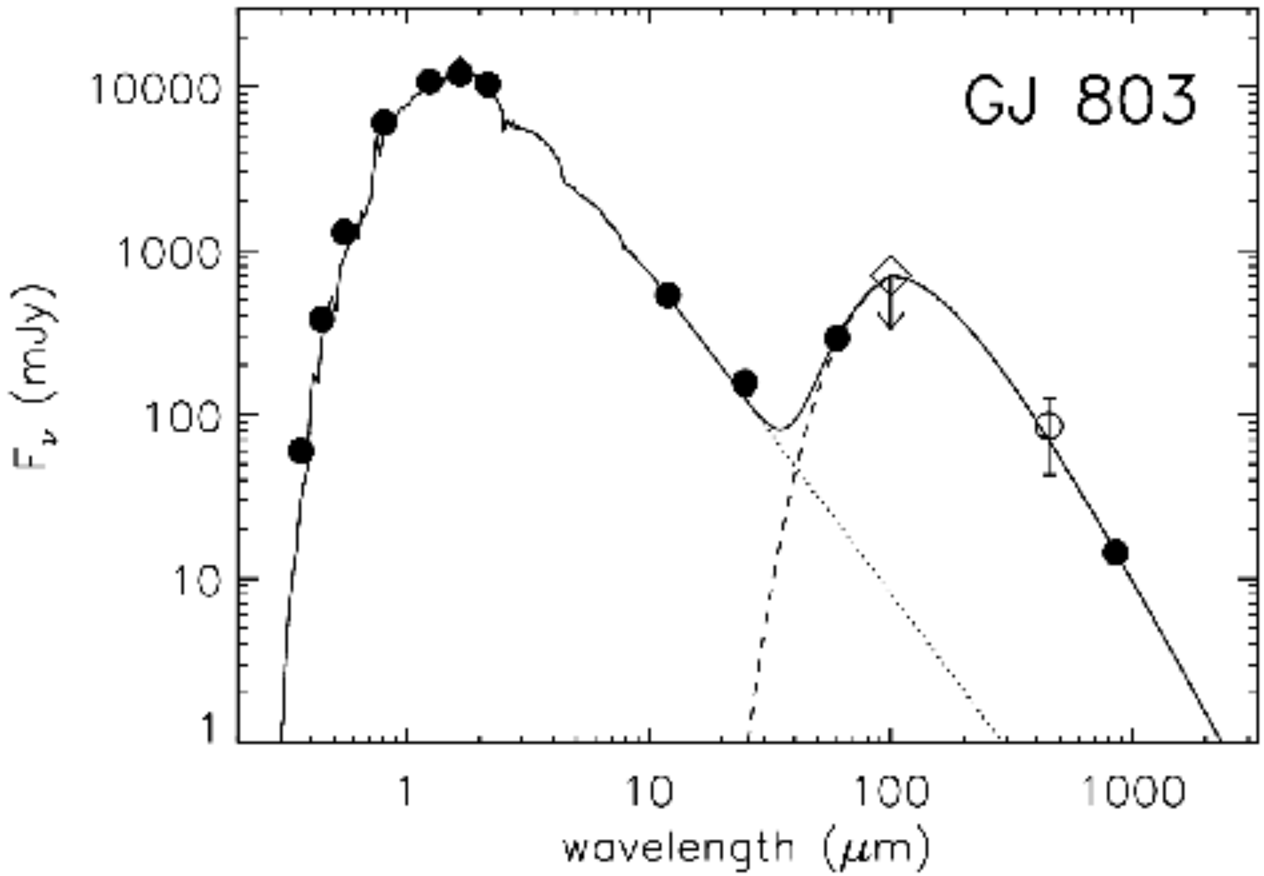
Leftovers

Gas is eventually captured or pushed out by wind from the star, but dust and planetesimals remain

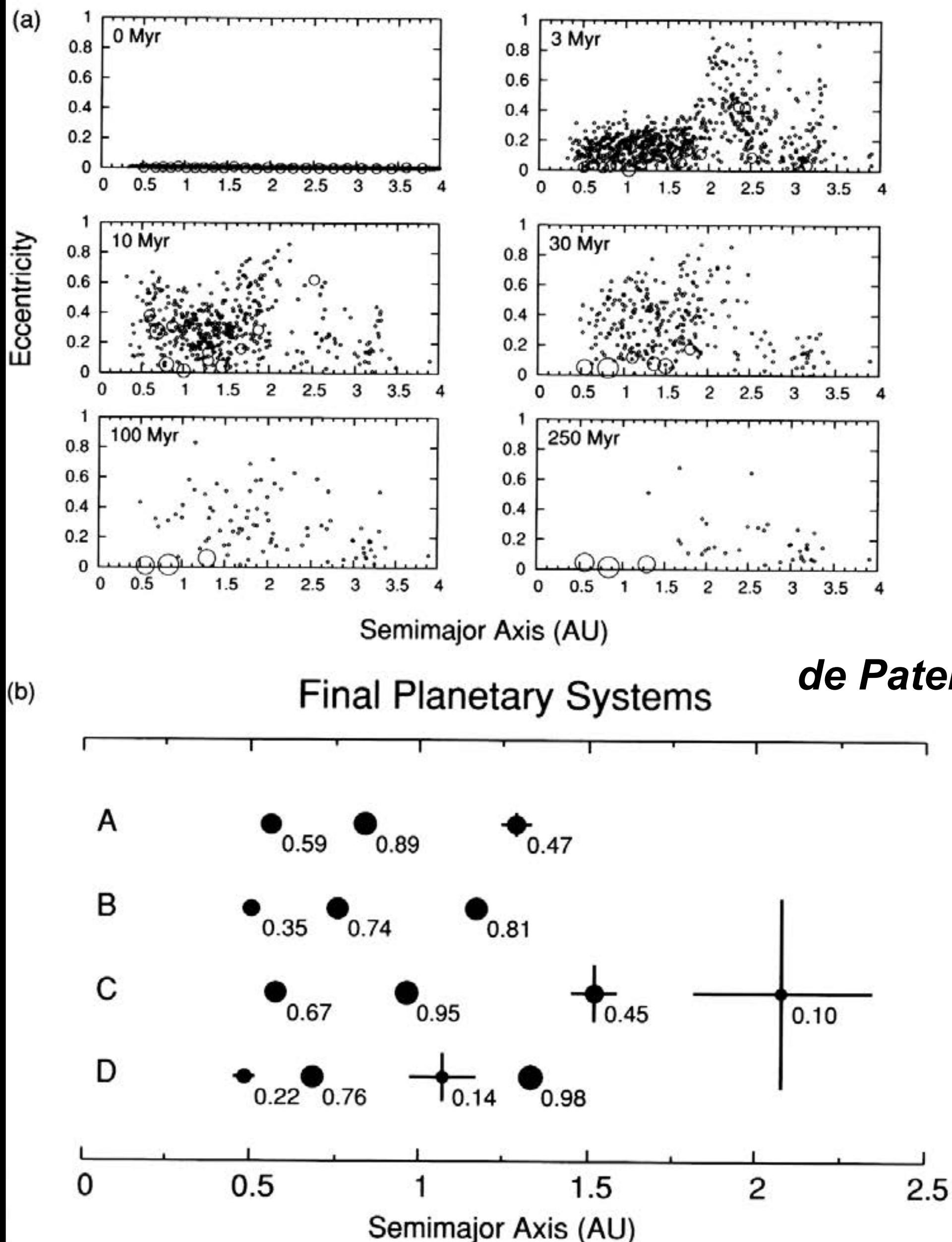
→ Late collisions form "debris disks"



Debris disks → infrared excesses



The randomness of it all…



Physical properties also affected by randomness of late accretion

- ***Rotation rates/obliquities***
- ***Bulk composition (Mercury)***
- ***Surface topography (Mars)***

de Pater & Lissauer (2010)

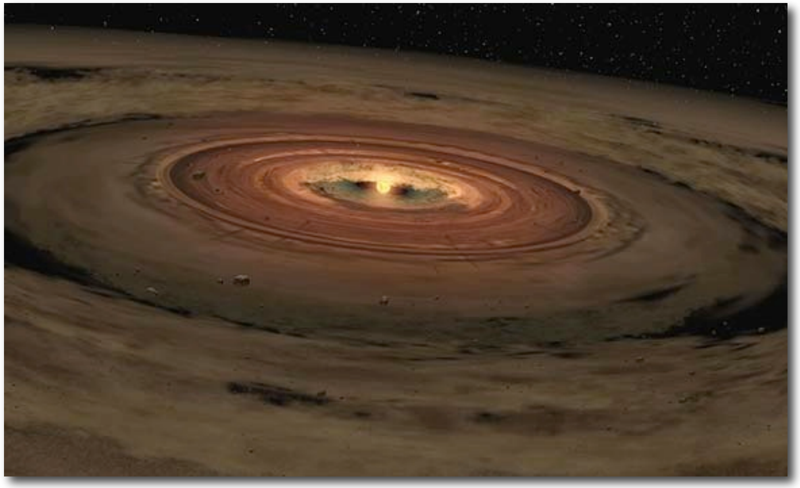
Giant planet sizes/orbits also influenced by random chance…

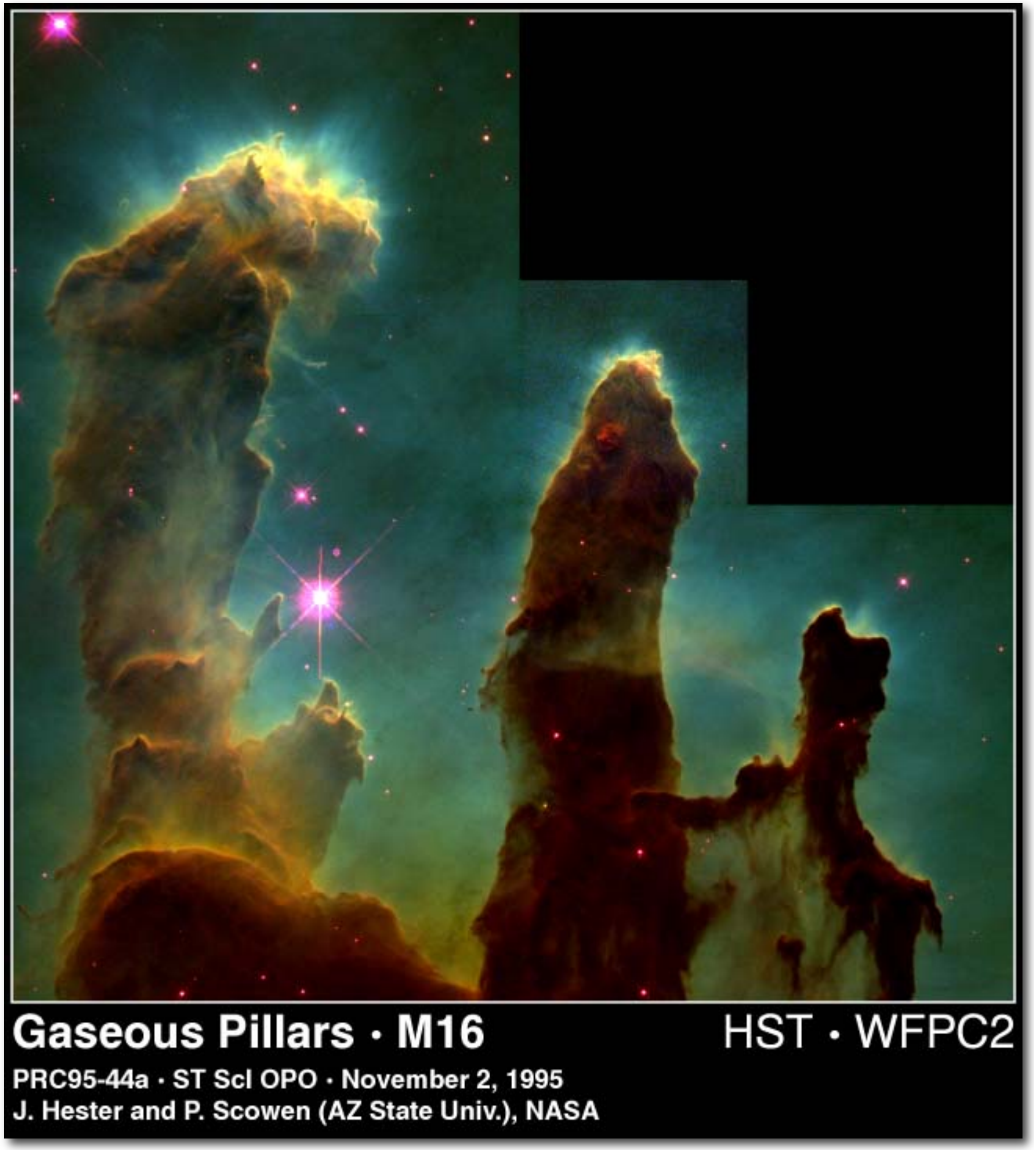
Solar System/Planet Formation

Gas Clouds
to Stars/Planets

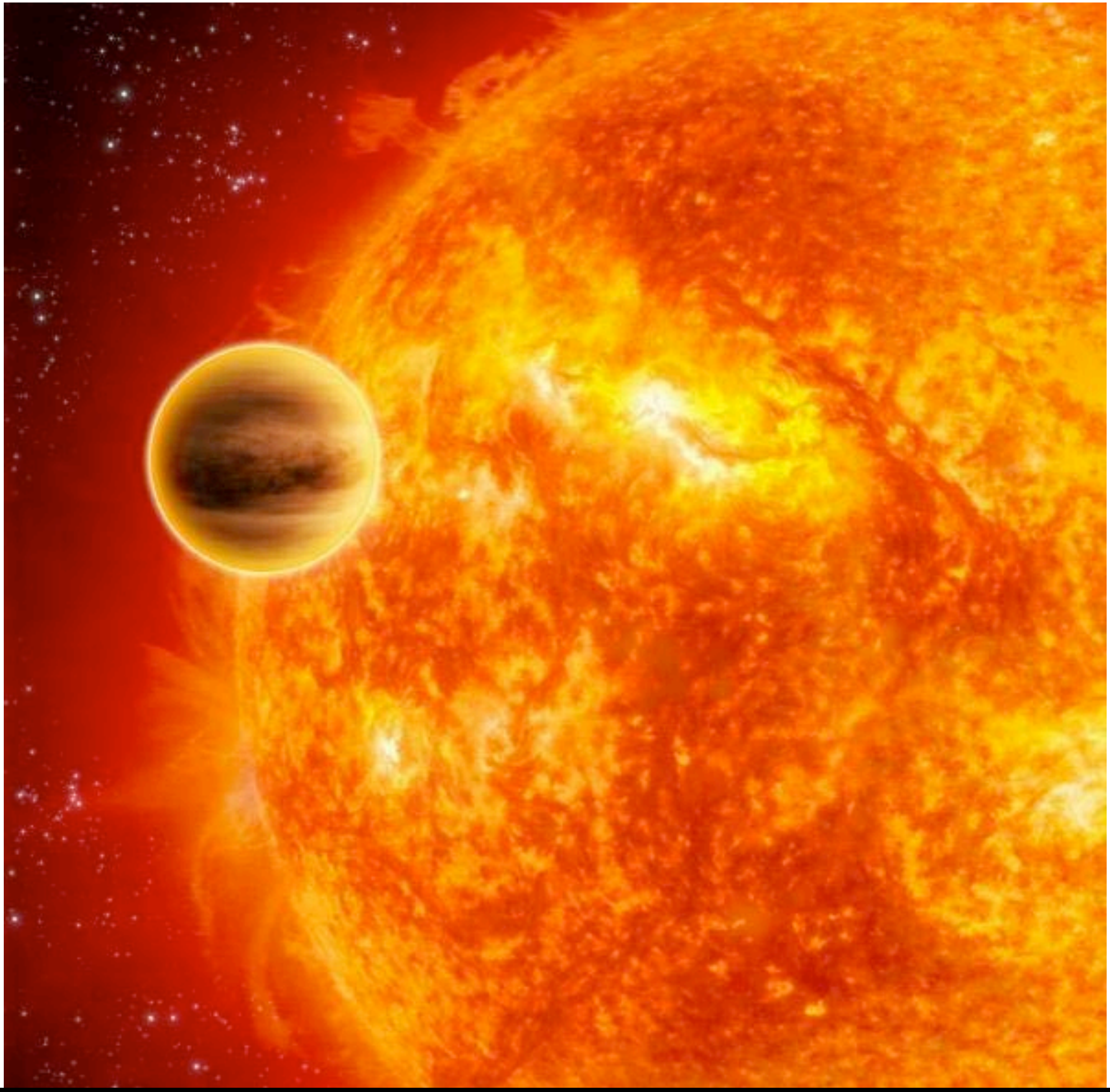
Planet Migration

Satellite Formation

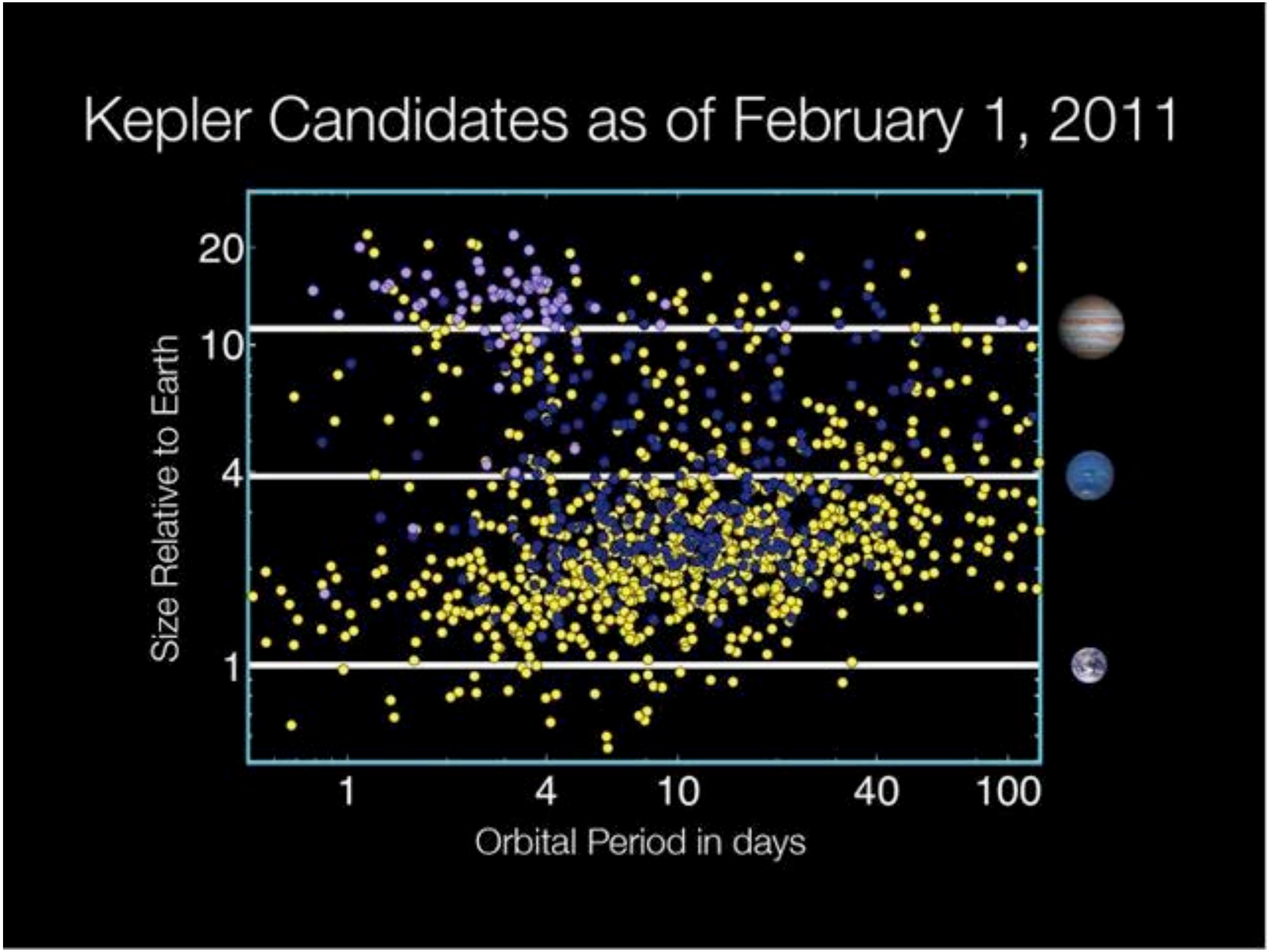




Close-in Giant Exoplanets → Migration



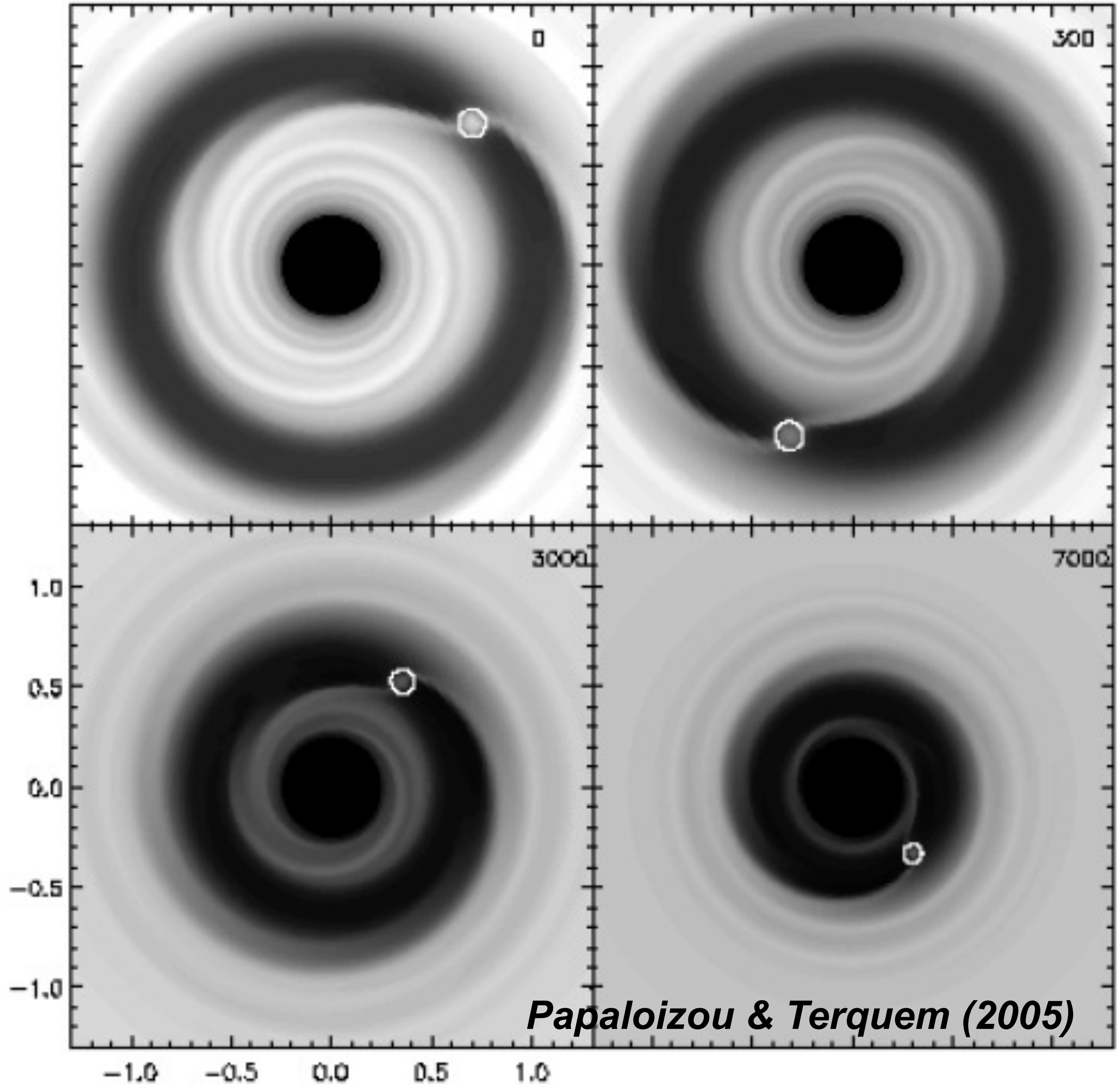
Close-in Giant Exoplanets → Migration



Inward Planet Migration

• **Probably through angular momentum exchange with disk gas**
  - **Type II: planet orbits in disk gap**
  - **Type I: no gap**

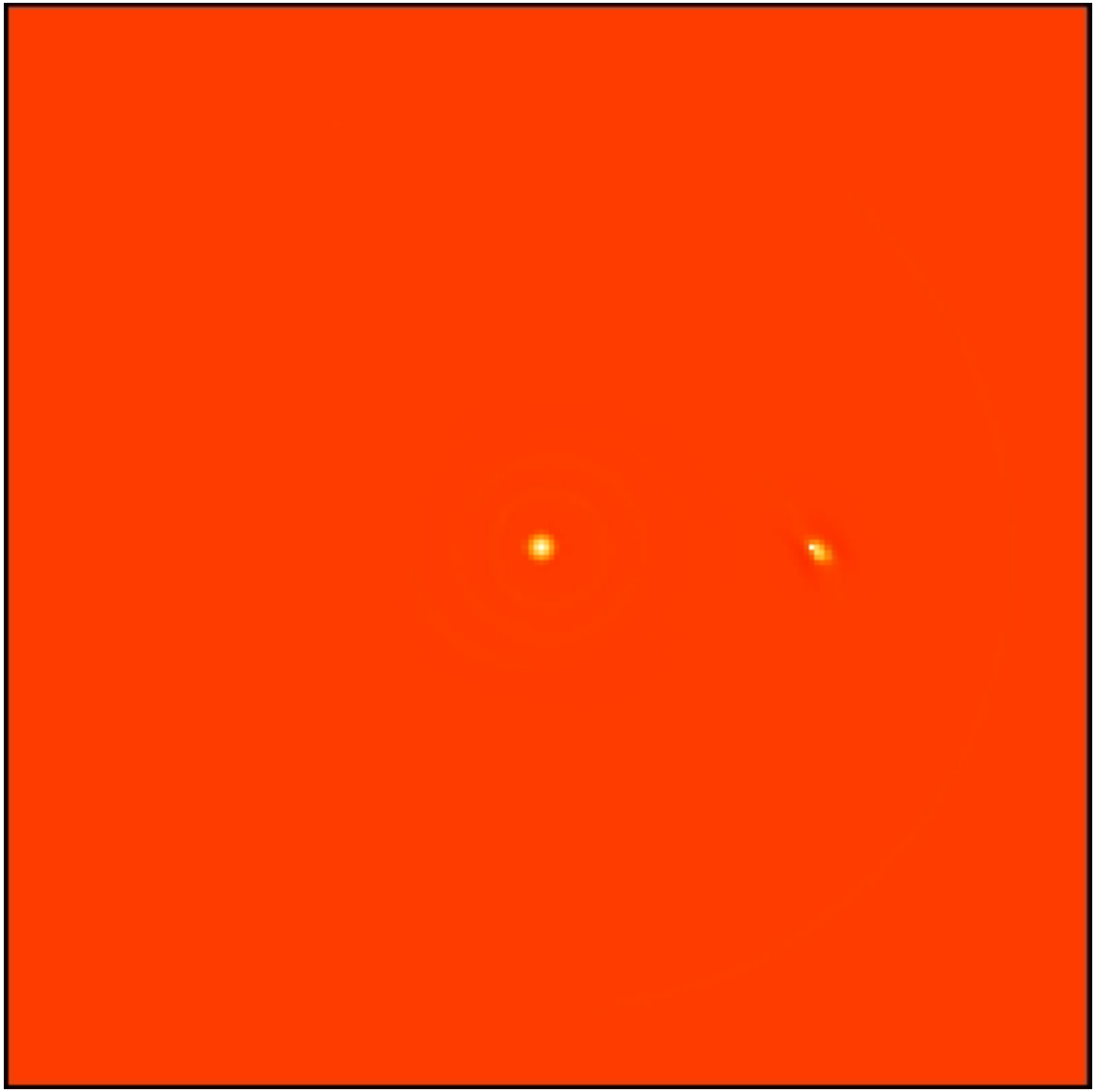
• **Stopping migration before planets merge with the star may require concurrent nebula dissipation**



Papaloizou & Terquem (2005)

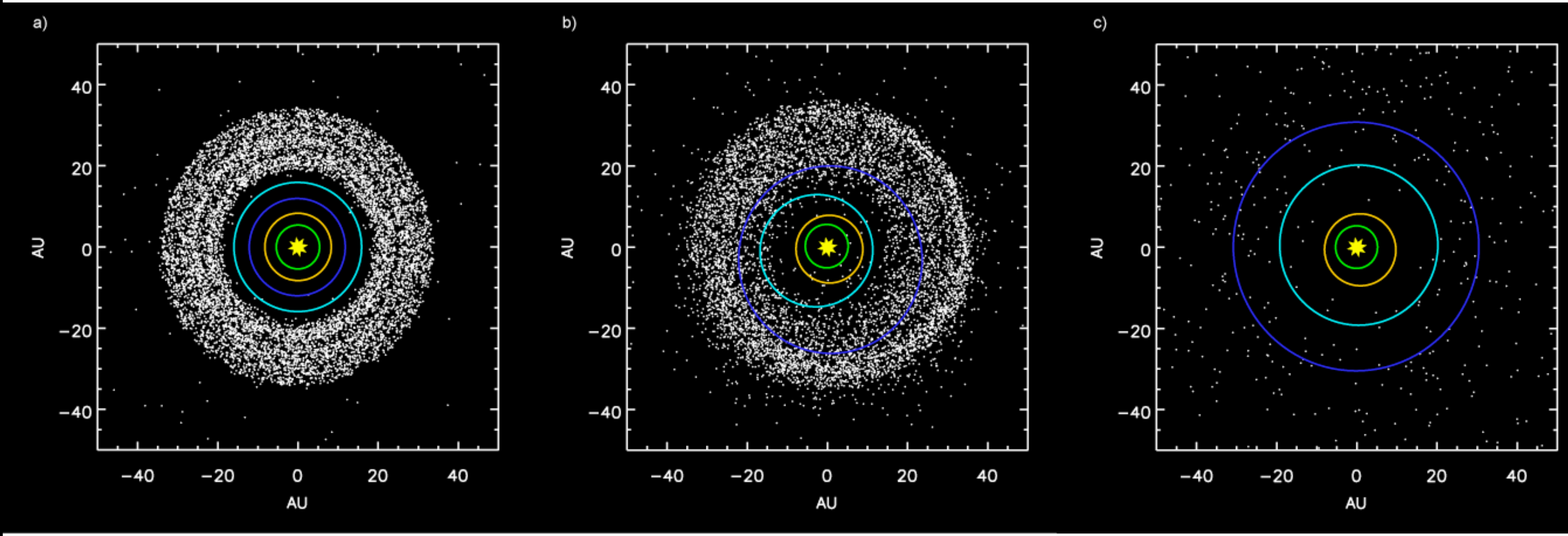
Inward Planet Migration

1.5M_{Jup} planet in 0.02$M_{\odot}$ disk(MMSN): ~100 orbits ending with simulated gas dispersal



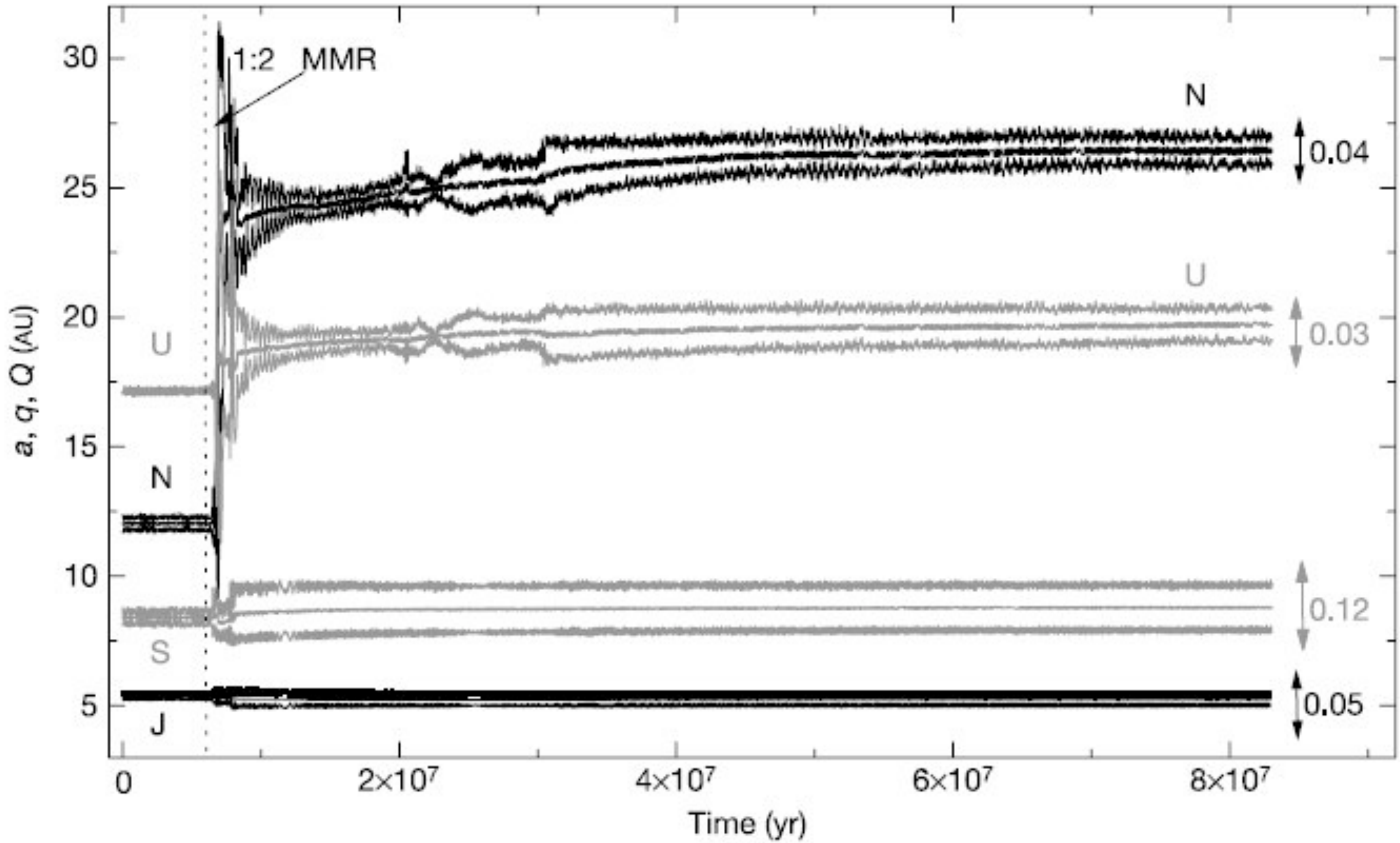
http://planets.utsc.utoronto.ca/~pawel/planets/movies.html

Outward Planet Migration: Nice Model



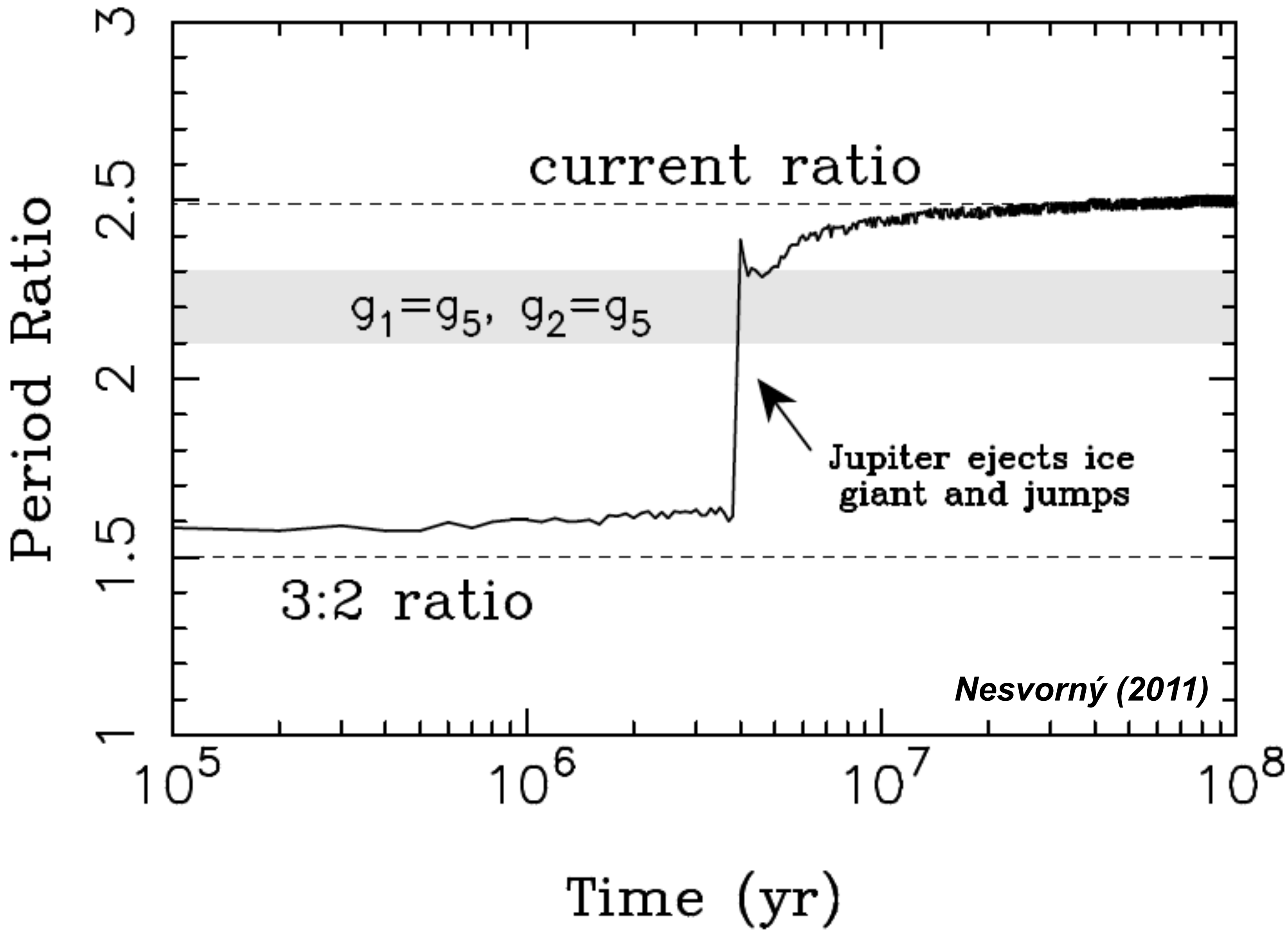
- **All planets formed at <20 AU (high density, short orbital periods)**
- **Outermost planet (Uranus?!) interacted with KB planetesimals, typically "passing" them inwards to interact with other planets**
- **Interactions with Jupiter cause ejection to Oort cloud or beyond**
- **Reflex planet migrations cause Jupiter and Saturn to cross 2:1 resonance → mayhem!**
  - ***Uranus and Neptune move way out, switch places?!***
  - ***Planetesimals scattered into inner solar system (LHB)***

Outward Planet Migration: Nice Model

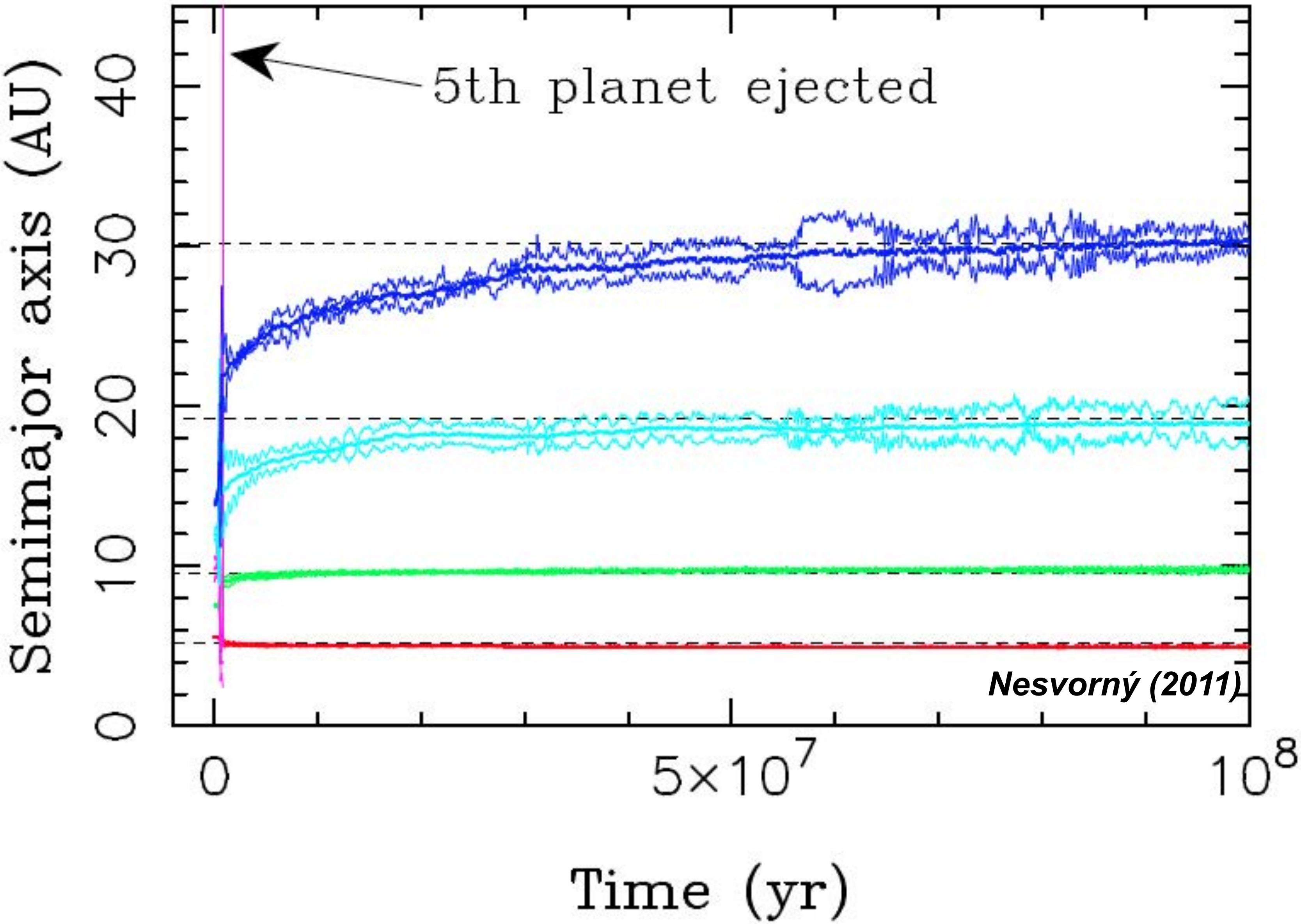


Problem: Terrestrial planet destabilization

Solution: 5th planet!?



Ejection of a 5th giant planet?

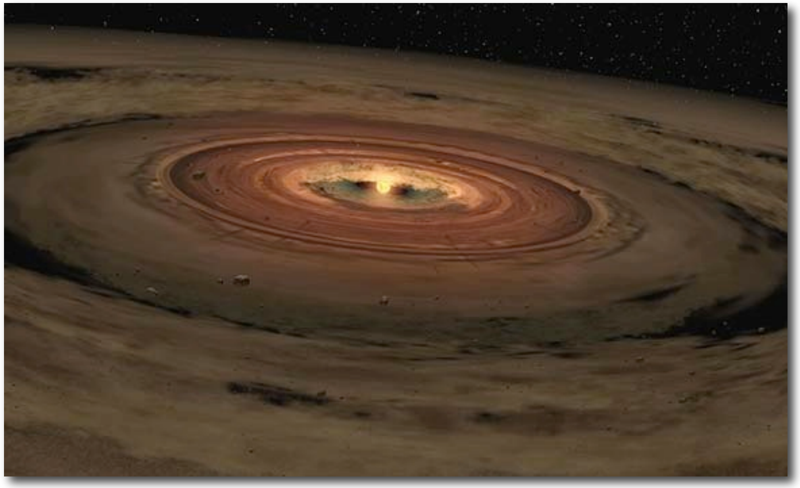


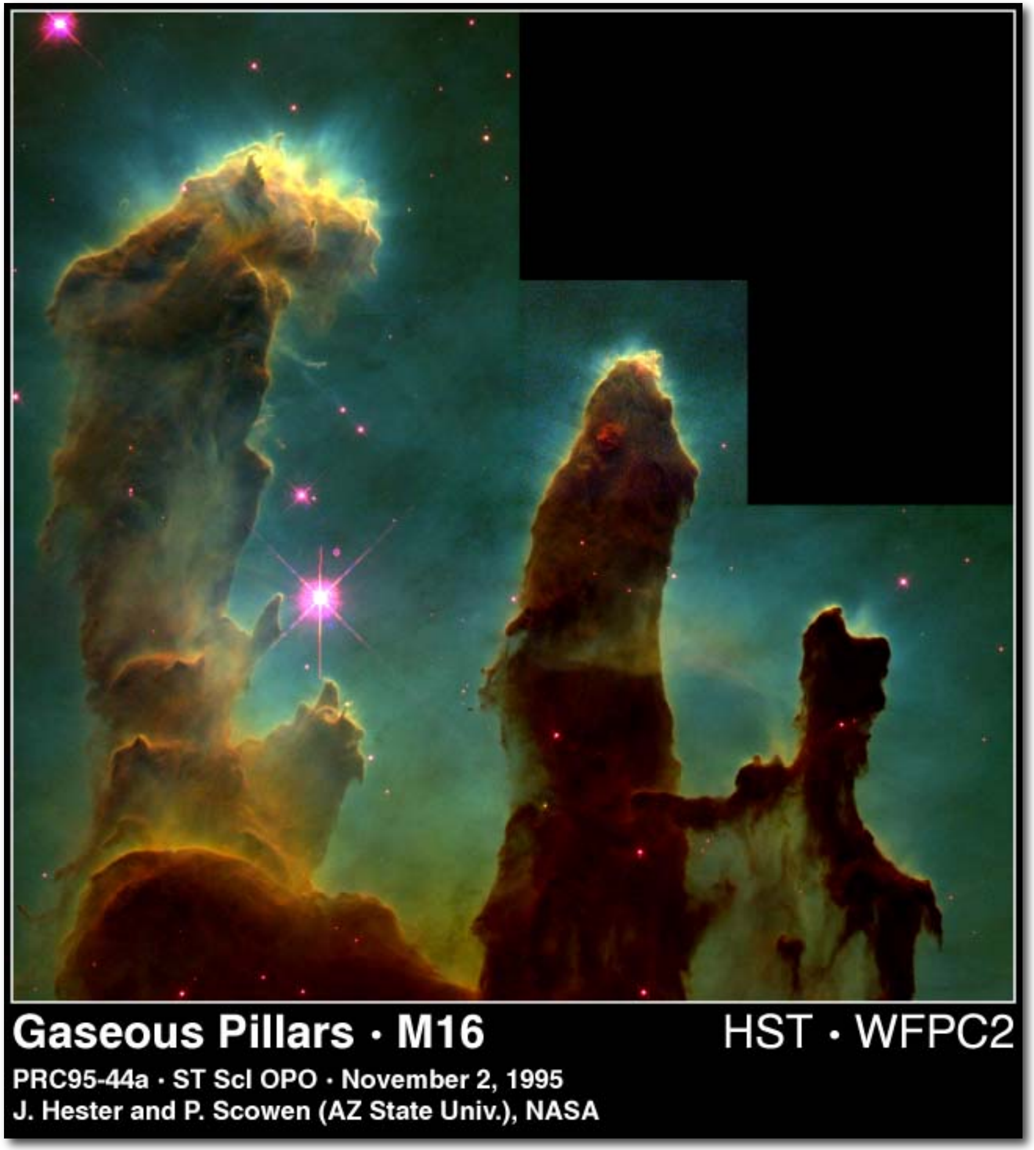
Solar System/Planet Formation

Gas Clouds
to Stars/Planets

Planet Migration

Satellite Formation

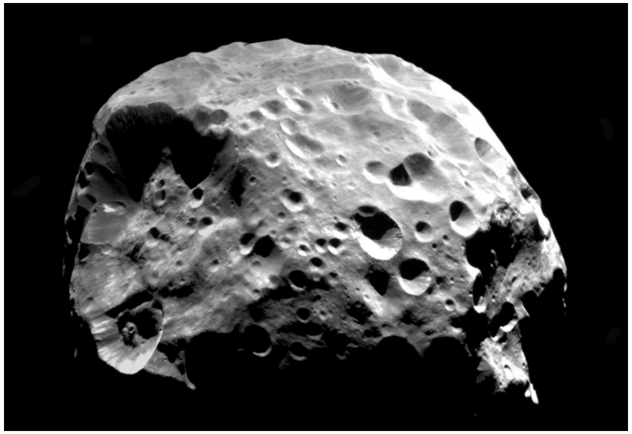




Satellite Formation Mechanisms

- **Circumplanetary accretion disks (“regular satellites”)**

- **Capture (“irregular satellites”)**

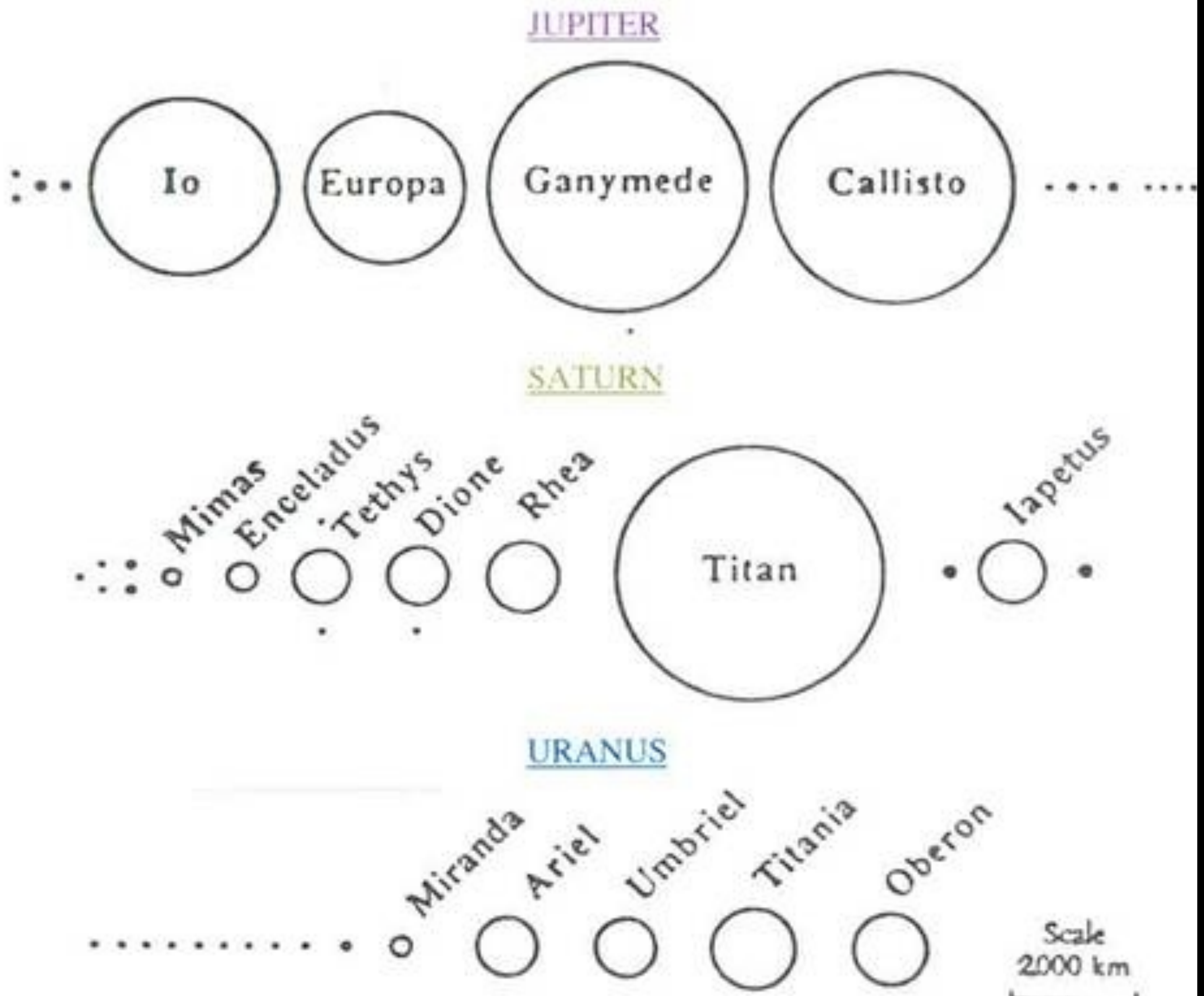


- **Giant impacts**

Formation of Regular Satellites

- **Regular Satellites:**
  - $M_s \sim 10^{-4} M_p$
  - $a_s < \sim 20\text{-}30 R_p$
  - $e, I \approx 0$

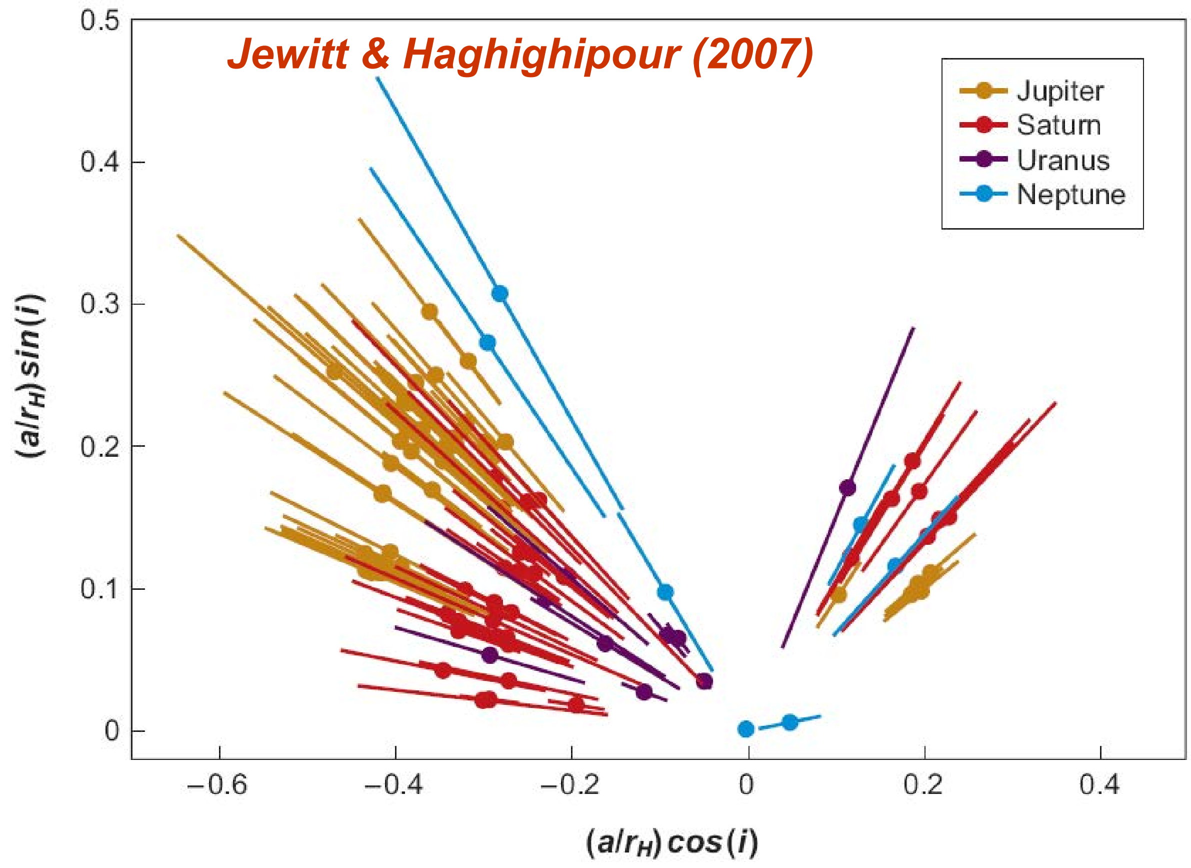
- **Form in "subnebula" of ~solar composition?**



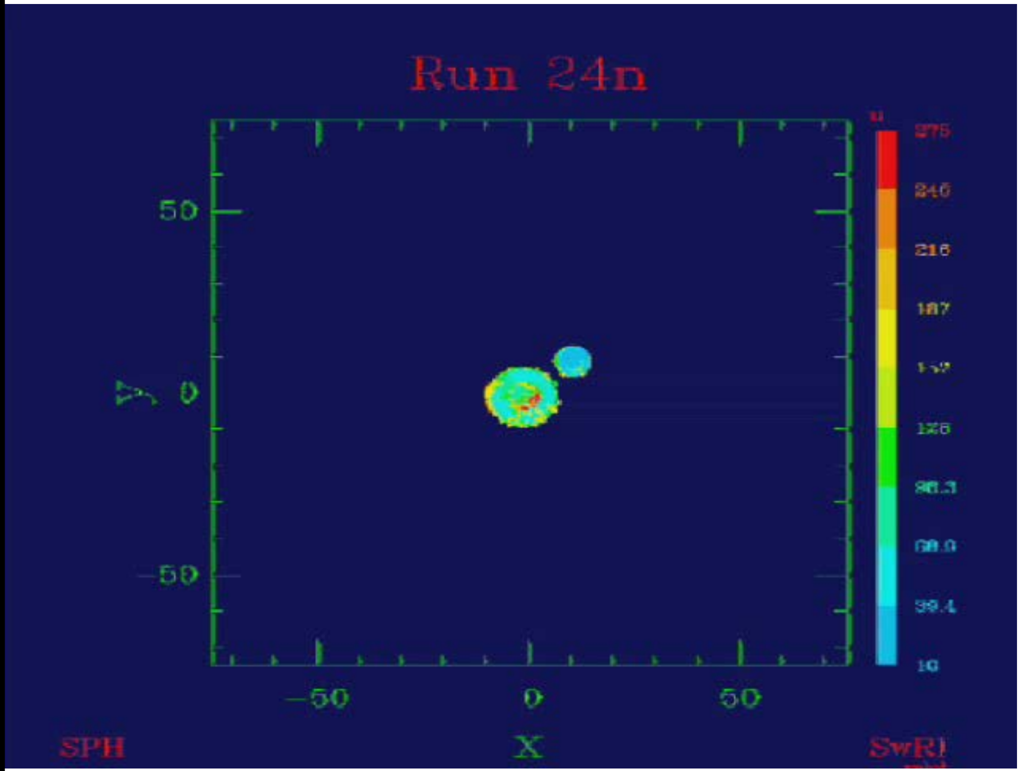
Capture of Irregular Satellites

- Irregular Satellites: small, distant, eccentric and/or inclined (often retrograde)

- Capture due to 3-body interactions (collisions or scattering) most likely, probably early



The Oddballs: Formed by Impact?



• Earth's Moon ($\sim10^{-2} M_{Earth}$) (Canup, 2004)

• Charon ($\sim10^{-1} M_{Pluto}$) (Canup, 2005)

For our Moon, this explains:

- Age (~4.4 – 4.53 Ga)
- Low volatile content
- Low bulk density (minimal iron core)
- Similar oxygen isotope ratios to Earth
- Early proximity and fast rotation of Earth